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# System Engineering Techniques for Establishing Balanced Design and Performance Guidelines for the Advanced Telerobotic Testbed

W.F. Zimmerman and J.R. Matijevic  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

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## 1. Abstract

Research and development projects have characteristically followed development processes structured around well-defined, but loosely organized, research goals. This particular approach differs from the standard, application-specific, product development found in the private sector. Nevertheless, research and development often follows a less defined application route because of the substantial amount of technical risk associated with its research goals. Novel system engineering techniques have been developed and applied to establishing structured design and performance objectives for the Telerobotics Testbed that reduce technical risk while still allowing the testbed to demonstrate an advancement in state-of-the-art robotic technologies. To establish the appropriate tradeoff structure and balance of technology performance against technical risk, an analytical data base was developed which drew on 1) automation/robot-technology availability projections, 2) typical or potential application mission task sets, 3) performance simulations, 4) project schedule constraints, and 5) project funding constraints. Design tradeoffs and configuration/performance iterations were conducted by comparing feasible technology/task set configurations against schedule/budget constraints as well as original program target technology objectives. The final system configuration, task set, and technology set reflected a balanced advancement in state-of-the-art robotic technologies, while meeting programmatic objectives and schedule/cost constraints.

## 2. Introduction

Funding limitations in both private and government sectors often make it difficult for research and development environments to operate totally independently of mainstream applications of potential products resulting from the research. Similarly, the Telerobotics Testbed, a research and development effort, is being viewed as a source of advanced seed robotic technology for the Space Station Flight Telerobotic Servicer (FTS). The near horizon for first-element launch (FEL) and initial operational capability (IOC) (i.e., the early to mid-1990's) places some pressure on the testbed breadboard effort to tailor its technology thrusts, and potential applications, towards these near-term developments. One of the challenges associated with defining the testbed breadboard development program is finding the appropriate balance between establishing an aggressive technology development program, yet maintaining a viable application channel with the Space Station FTS environment and development schedule. From an operations research viewpoint, this situation represents the classical problem of satisfying several competing objectives with limited resources. Although it would appear that classical linear programming or "branch and bound" optimization techniques could be applied as solution structures to the competing objectives problem, in fact the introduction of key intangible (i.e., not readily quantifiable) variables made the solution of the problem not immediately amenable to a rigorous mathematical representation. Nevertheless, optimization techniques such as branch and bound provided a structure for obtaining progressive, feasible sets of solutions that could be independently examined until a "reasonable" solution to the performance versus technical risk tradeoff problem was found. The following paragraphs discuss 1) how the overall problem and solution structure was developed, 2) the tradeoff variables (both tangible and intangible), 3) the rationale behind the derivation of feasible solution sets, 4) the selected feasible solution and associated bounds, and 5) supporting data.

## 3. Problem Definition and Solution Structure

The first step in obtaining a solution to the competing objectives problem was to establish a concise definition of the objectives and constraints. The major variables that needed to be satisfied in the tradeoff process were as follows:

1. Programmatic technology objectives - Addresses the overall approved technology goals jointly agreed to by the research sponsor (NASA Office of Aeronautics and Space Technology [OAST]) and the responsible research organizations (Jet Propulsion

Laboratory, Langley Research Center, Marshall Space Flight Center, Johnson Space Center, Ames Research Center, Goddard Space Flight Center, and Massachusetts Institute of Technology.)

2. Viable mission task set - Refers to the development of an application environment which is both feasible (in terms of technology performance capabilities and constraints) and representative of a real-world use of the technology.
3. Schedule - Addresses the time constraint associated with completing the technology objectives as part of normal programmatic planning/assessment, and meeting other outside schedule needs such as the PTS FEL/IOC development and qualification milestones.
4. Cost - Refers to the budgetary constraint imposed at the programmatic control organization (NASA OAST).
5. Performance - Addresses the capability of the hardware and software to actually execute and successfully complete a selected task set (a measure of technical risk).
6. Technology availability - Refers to the actual state of maturity of a given technology element as measured against state-of-the-art and in the context of the overall system capability to perform a selected task set.

In examining each of the above variables in terms of "objectives" and "constraints" it became clear that the first two variables (technology objectives and mission task set) represented the primary optimization objectives. The ability of the program, and actual system design, to reach these objectives would be subject to the constraints imposed respectively by schedule, cost, hardware and software performance limitations, and the relative states of achievable maturity of the component technologies. Mathematically, the optimization problem could be stated as follows:

$$\max_{T, a} \sum_{t=1}^n \sum_{a=1}^m T_{t,a} \quad (1)$$

subject to,

$$\sum_{t=1}^n \sum_{a=1}^m s_{t,a} \leq S_T \quad (2)$$

$$\sum_{t=1}^n \sum_{a=1}^m c_{t,a} \leq C_T \quad (3)$$

$$\sum_{t=1}^n \sum_{a=1}^m p_{t,a} = P_T \quad (4)$$

$$\sum_{t=1}^n \sum_{a=1}^m t'_{t,a} > T'_T \quad (5)$$

The above formulation basically states that it is desirable to maximize the overall targeted technology capability (T) and feasible application task performance capability (a) subject to 1) the respective technology development schedules (s) not exceeding the overall programmatic schedule (S), 2) the respective technology development costs (c) not exceeding the overall programmatic cost ceiling (C), 3) the respective technology performance limitations (p) being commensurate with the overall programmatic technology performance objectives (P), and 4) the aggregate achievable technology maturities (t') being greater than the overall state-of-the-art technology level (T'). The above formulation serves the purpose of providing a clear statement of the competing objectives problem. However, from a practical standpoint it is very difficult to actually measure all of the above variables. For example, the technology objectives and application task set do not lend themselves to quantification in the same sense as cost and schedule. Similarly, setting the state-of-the-art technology baseline and comparing the composite testbed technology maturity level against that baseline is also difficult to quantify. Therefore, these three variables represented important, but intangible variables. The remaining variables (schedule, cost, and performance) represented the tangible variables.

In order to cope with the intangible variables, a more empirical approach was taken to structuring the optimization problem. Keeping the objective function and constraints the same, a modified branch and bound technique was formulated that provided a tradeoff structure that could accommodate both quantitative and qualitative representations of the objective and constraint variables.

Therefore, the next step in formulating the solution was to tailor the branch and bound optimization structure to handle both qualitative and quantitative decision data. By definition, the branch and bound optimization technique starts by setting a bound on the objective function (Ref. 1). Next, the technique requires that the set of all feasible solutions (i.e., in this case the technology and application task sets) first be partitioned into several subsets. Because the objective of the exercise is to maximize the chances of meeting the original technology objectives while exercising those technologies in the most robust application environment possible, any subset of alternative technologies and applications that does not meet the original objectives is eliminated. Each subset is evaluated against the objective function and constraints until a solution is found that meets all conditions. In the absence of a clear-cut analytical solution to the competing objectives problem, a decision network was designed that allowed the subset partitioning and evaluation steps to be completed in exactly the same spirit of the branch and bound solution structure outlined earlier. This decision network is shown in Figure 1.

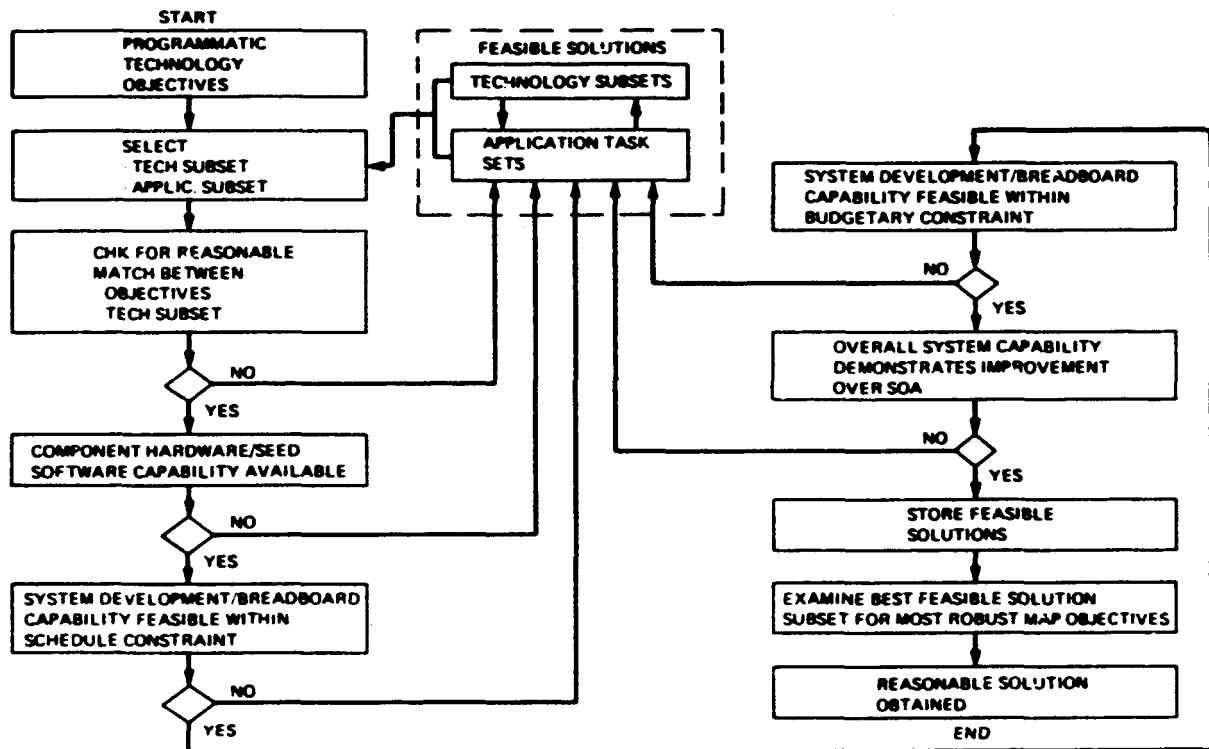


Figure 1. Feasible Solution Decision Network

Figure 1 displays the serial decision process that allows the subsets of feasible solutions to be filtered out of a large group of candidate technologies and applications. Note that the decision structure is designed to be an "and" decision gate so that both objectives and constraints must be simultaneously satisfied (as implied in eqs. 1-5) to obtain a "reasonable" solution. It should also be noted that although the above structure provides a reasonable solution, by design, it does not yield the rigorous, analytical numerical solution that linear programming or classical branch and bound optimization techniques yield.

#### 4. Data Base

The above objective and constraint variables were supported by an extensive quantitative and qualitative data base. These various data bases are summarized below:

1. Programmatic technology objectives (qualitative) - The programmatic objectives were established at the onset of the testbed project (Ref. 2). The overall Phase 1 (FY 1987/1988) program objectives were 1) automated object acquisition and tracking, 2) video-based location/orientation of simple objects, 3) off-line coordination-level telerobot activity planning, 4) an architecture for coordinated planning/diagnostics for telerobot command and control, 5) dual-arm coordinated control with hybrid force/torque, position, and rate feedback, 6) dual force reflecting hand controllers, stereo display, and fused force/torque video feedback for teleoperation, 7) an architecture for run-time control of the telerobot with the capability to interpret and execute task primitive commands generated by the activity planner, and 8) a

- distributed, multi-processor command and control hierarchy with the capability to be modularly upgraded and provide simple error recovery.
2. **Viable mission task set (qualitative)** - A fairly extensive literature search was conducted to establish an application task set in which to develop and test the various technologies and overall telerobot system (Refs. 3-13). At the onset of this portion of the analysis it was assumed that the most viable application of the telerobot, in the near term (per the FTS augment to extravehicular activity), would be for on-orbit assembly and servicing. Therefore, the application task set was sought primarily in planned, or historical, on-orbit servicing activities. Skylab and Shuttle historical experiences were most useful. Unfortunately, proposed Space Station-related servicing missions such as Space Telescope were not defined to a level of detail that would facilitate an accurate mapping between servicing functions and needed technologies. Ultimately, the Solar Max repair mission provided a full array of detailed servicing tasks that was sufficiently granular and representative of probable FTS servicing activities so as to provide a good starting application subset.
  3. **Schedule (quantitative)** - The schedule constraints imposed on the project were 1) a demonstration of core technology elements by end of FY 1987, 2) followed by a full integrated demonstration of the complete telerobotic breadboard system by end of FY 1988.
  4. **Cost (quantitative)** - The cost constraint for the project for the three-year effort starting FY 1986 (including funding outside leverage from other NASA centers, industry, and universities) was projected to be approximately \$20M.
  5. **Performance (quantitative)** - The performance envelope of the technologies was derived from the actual physical capabilities and constraints of the hardware and software used in the research laboratory. For example, the vision subsystem was able to provide fixture location to within 1 mm and resolve unoccluded fixtures (within the constraints of the internal object model software) such as small panels, handles, or bolt heads. The PUMA 560 arms (typical of nationwide laboratory hardware) used in the control technology development, had specified reach envelopes, joint movement constraints, and load-handling capabilities. Once a task set, object library, and task data base (object locations, forces, torques, etc.) were established, the system performance was simulated on an IRIS dynamic computer display system to obtain a rough estimate of system and application feasibility. A single frame of the dual arm servicing simulation is shown in Figure 2.

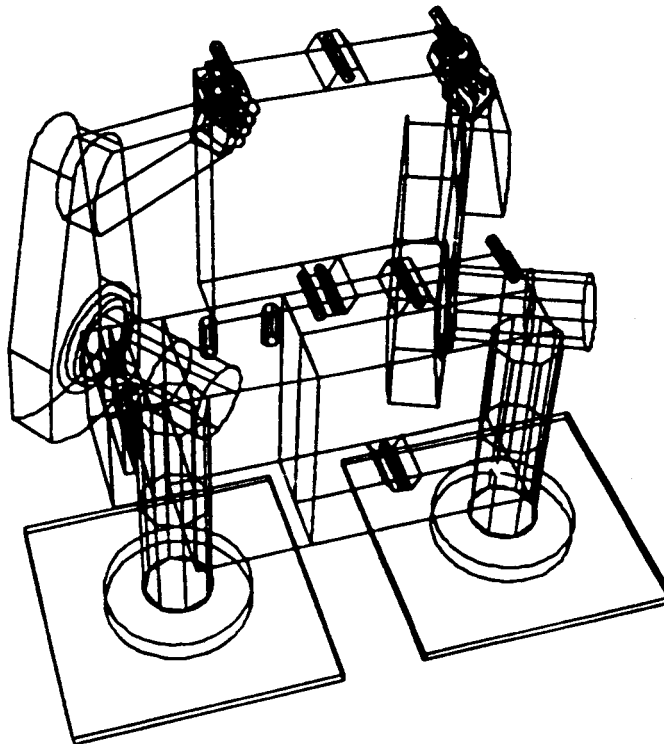


Figure 2. Dual Arm Telerobot Servicing Simulation (IRIS)

6. **Technology maturity and availability (qualitative)** - When faced with hard schedule and budgetary constraints, projects must set their sights on technology goals which represent both an advancement as well as a realistic, achievable objective. Although some studies have been done which suggest both maturity levels and time frames for the

breadboard and fully operational versions of advanced automation technologies (see Refs. 14, 15, and 16), generally it is extremely difficult to bound, or constrain, a qualitative variable using an upper bound which has a fairly large variance itself. This problem is compounded when considering other constraints such as setting technology goals that enable the breadboard development (i.e., the FY 1988 schedule constraint) to transfer technology in a timely manner to both the FTS brassboard and fully operational configurations. This development constraint implies that a distinct time frame is needed to move through all the development stages as shown in Figure 3.

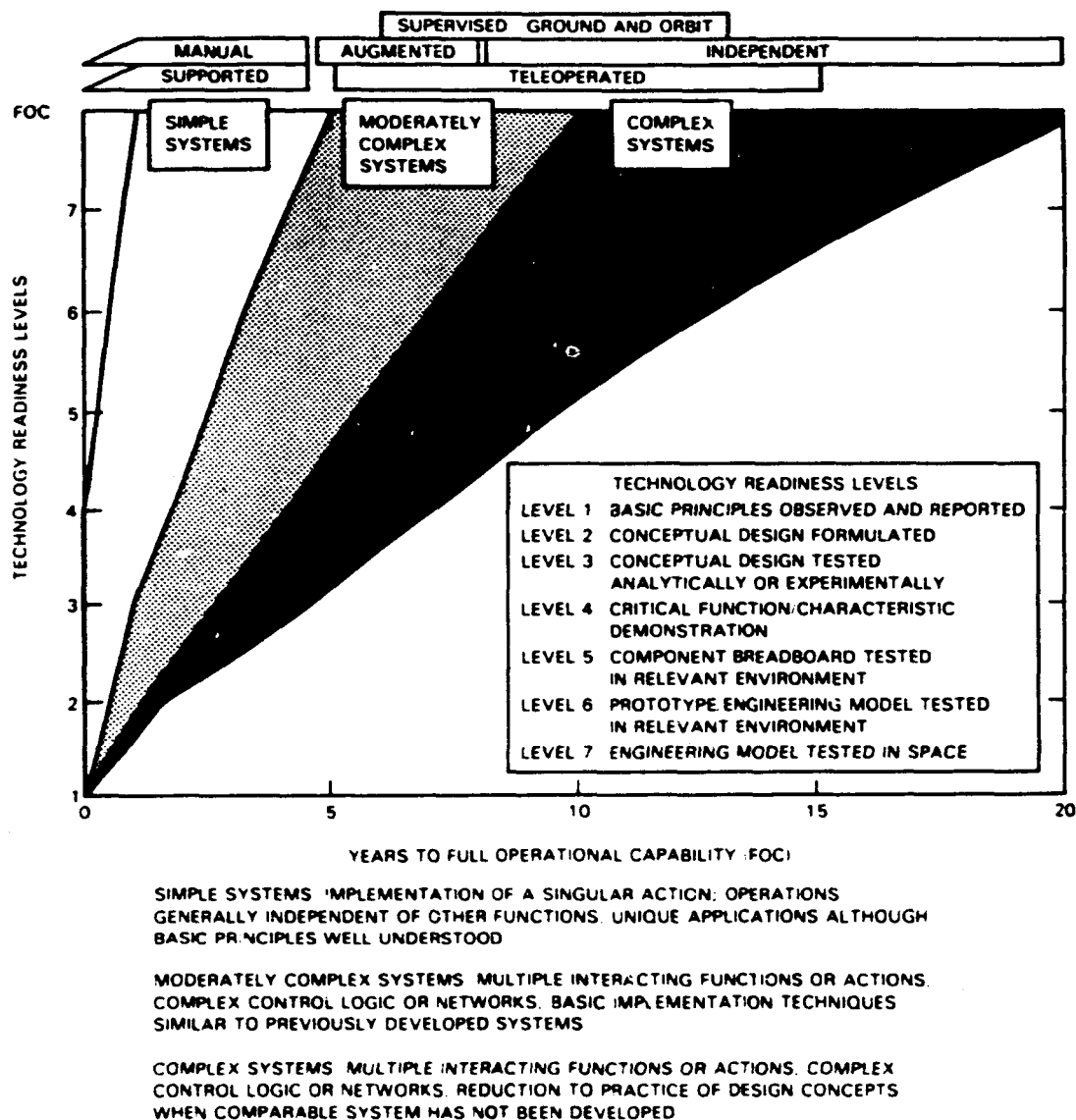


Figure 3. Technology Development as a Function of Readiness Levels and Time

Therefore, rather than establishing an upper constraint for the maturity variable, a state-of-the-art baseline was established and used as a known, lower bound. The state-of-the-art lower bound then simply had to be exceeded while simultaneously providing a viable breadboard configuration that could appropriately meet FTS schedule constraints. The state-of-the-art baseline was set against available, working engineering models and included 1) sensing and perception - simple labeled and unlabeled object tracking with manual acquisition; 2) task planning/reasoning - off-line sequence generation and no well-structured human-robot cooperative plan generation; 3) operator interface - dual arm teleoperation, limited real-time computer graphic displays, stereo vision, limited external state sensing, limited operator/workstation integration, no traded control between teleoperation and autonomous states; 4) control execution - model-based single arm control or teach pendant, leader-follower dual arm position control, limited hybrid control, 5) control architecture

and integration - limited hierarchical control, centralized processing/memory, coordination level control in structured manufacturing environments, distributed processing architectures, teleoperation and autonomous control not traded, limited hierarchical error management.

## 5. Tradeoff Results

The last step in the analysis was to execute and re-execute the Figure 1 decision structure until a reasonable solution was obtained which met both the objective function and constraints. The iteration process commenced with publishing an application task set (drawing on the full Solar Max servicing scenario) along with the projected commensurate implementation technologies. Immediate problems were encountered because 1) the real-time reconfiguration task elements associated with main electronics box (MEB) exceeded the task planning capability of the system, 2) object masses and electric socket removal forces exceeded the load characteristics of the PUMA arms, 3) some component disassembly sequences exceeded the hardware and software control characteristics of the PUMA arms and control algorithms, and 4) the large array of geometric shapes associated with the servicing environment exceeded the vision system CAD data base. The servicing scenario was downscaled. The task-related objects were redesigned to accommodate the PUMA constraints and simplified.

In the manner described above, each application task set and corresponding technologies were reviewed with the various subsystem research engineers against schedule constraints, budgetary limitations, hardware/software limitations, and the state-of-the-art baseline until a subset of each was obtained which satisfied all the objectives and the constraints. The corresponding solution set is shown in Table 1 (Ref. 17).

Table 1. Telerobot Application and Technology Solution Subsets

Application Task Set	Technology
1. Capture/dock slowly rotating satellite (1 rpm)	Automated labeled object acquisition, tracking, dual arm servoing
2. Verify initial object in task sequence (MACS)	Automated stationary object verification
3. Remove star tracker covers on MACS	Teleoperation under alignment/accuracy/force constraints (dual arm)
4. Confirm auto sequence plan	Operator-AI planner interaction (operator can update object location, confirm plan, or update a task monitoring point)
5. Teleop traded off to auto, verify/grasp bolt wrench	Automated object verification, plan execution, hierarchical control with limited error recovery
6. Remove MACS retaining bolts	Automated object verification, hybrid force/position and force/torque control with trimming
7. Remove/replace MACS	Automated object verification, dual coordinated master/slave arm control, simple collision avoidance, position and rate control
8. Auto traded off to teleop for satellite repositioning	Dual arm teleoperation, position/alignment control (video, stereo, 6 DOF hand control, and voice camera control)
9. Remove MEB thermal blanket	Same as 8 above, handling flexible objects
10. Teleop traded off to auto, hinged panel door opened, simplified MEB electrical connectors removed, MEB removed and replaced	Same as 4 through 7 above, limited automated flexible object handling, precise automated control in simple obstacle field with guarded motion along an arc

The above table is somewhat abbreviated for summary purposes. However, the complete detailed application task set and technology correlation is provided in the Telerobot Testbed functional requirements (Ref. 17). By far, the largest improvements in the respective technologies over state-of-the-art revolved around the vision-based fixture update and its integration with the control execution, the integration of the planner with the control execution, the auto to teleop traded control, the dual arm coordinated control, and the distributed control hierarchical design with on-line (although simple) error management woven

throughout the hierarchy. The application task set, although simplified to meet performance and technology constraints, still provided a viable environment reasonably close to projected orbital replacement unit (ORU) removal/replacement FTS tasks. Finally, the selected technology subset was reasonably in-line with schedule/cost constraints; and, although composed of both state-of-the-art technologies and evolutionary (as opposed to revolutionary) improvements over other state-of-the-art technologies, the selected subset appeared achievable in a manner commensurate with supporting the out-year FTS development.

## 6. Conclusions

The revised branch and bound solution structure augmented with the supporting data bases and system simulation provided an excellent blueprint for obtaining a reasonable solution to an extremely difficult tradeoff problem. This technique has proven very useful for structuring the Telerobot Testbed research and development program to be sensitive to real-world demands and constraints. The technique is presently being employed to start negotiating and planning the 1990 demonstration.

## 7. Acknowledgments

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